RESPONSE OF ROBUST MUNITIONS
TO SECONDARY FRAGMENTATION

L. Javier Malvar
Naval Facilities Engineering Service Center
Port Hueneme, CA 93043

ABSTRACT

Sympathetic detonation (SD) criteria is being developed for the design of walls to prevent the propagation of accidental explosions. Magazines are being evaluated for increasing storage limits without compromising explosive safety. This can be accomplished via the installation of non-propagation walls to separate munitions and reduce the maximum credible event. Special walls, developed and certified under the High Performance Magazine program, will insure mitigation of SD. However for standard reinforced concrete walls, e.g. standard dividing walls, secondary fragments could result in SD of adjacent munitions. Criteria for prevention of sympathetic detonation between adjacent magazines is also being studied. Prevention of sympathetic detonation is currently feasible for robust, albeit sensitive, acceptors such as the MK82 bomb and the M107-155mm projectile in adjacent non-standard earth-covered magazines (with separation distances based on standard magazines).

Robust acceptor munitions were first numerically analyzed for peak explosive fill pressure and deformation from single concrete fragment impact. The acceptors considered were a M107-155 mm projectile, and a MK82 bomb. The numerical analyses were carried out using explicit, Lagrangian finite element models. The calculated response was compared to sympathetic reaction (SR) criteria and limited debris test data to determine debris mass and velocity thresholds for SR. The numerical study considered two sizes of spherical concrete debris fragments: 4 inch and 12 inch diameter (3 and 77 lbs respectively) at velocities from 200 to 1200 ft/s. Both test and analysis results for the thick-case M107-155mm projectile showed a burn threshold of 800 ft/s for large fragments. The projectile was shown to be insensitive to the 3-lb fragment at usual debris velocities. The thick-case MK82 bomb was shown analytically to be about as insensitive as the M107-155mm projectile. With a rigid backwall, the burn threshold for the three acceptor munitions was reduced to 600 ft/s for large fragments.

Numerical analyses were then conducted to assess the response of three MK82 acceptors located in-line and impacted by a concrete headwall at velocities of up to 110 ft/s. This headwall velocity corresponds to a 500,000 lb detonation in an adjacent magazine. These preliminary numerical analyses indicate that the MK82 acceptors would be subjected to pressures and deformations well below established reaction thresholds and no sympathetic reaction would be expected.

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1. INTRODUCTION

Nonpropagation walls (NPW's), such as the 12-inch reinforced concrete "substantial dividing wall", the US Air Force Buffered Storage wall, and the US Navy High Performance Magazine (HPM) wall, are used in explosives facilities to mitigate the explosion effects of donor munitions and thereby prevent sympathetic detonation (SD) of acceptor munitions. The greatest risk for SD of acceptors is the impact and penetration of primary fragments from the donor. Primary fragments can be easily mitigated with properly designed barriers. However, since it is impractical to design the NPW to structurally survive the donor loads, the impact of the NPW debris on acceptors becomes the critical mechanism for SD. This secondary debris impact creates direct shock on the acceptor's explosive fill that could exceed the critical pressure for shock-detonation transition (SDT). In addition, the debris impact could cause large deformations and rupture of the acceptor that could result in sympathetic reaction (SR) with the possibility of deflagration-detonation transition (DDT) or unknown stimulus - detonation transition (XDT). SR is used to identify any chemical reaction of the acceptor explosive fill, such as burning, deflagration, and detonation. This paper first presents an analytical study of the effects of single concrete debris on selected munitions, compares the results to available test data, and provides a limited preliminary threshold sympathetic reaction (SR) criteria. This SR criteria is developed for single concrete fragment impact of acceptor munitions in terms of fragment velocity and mass. A limited study on the prevention of SD between adjacent earth-covered magazines in then detailed.

2. BACKGROUND

Limited SR criteria is available for debris impact on acceptor munitions. Tests conducted with concrete rubble, gravel and sand debris [1] indicated that velocities of 350 ft/s could result in SR of lightly cased explosive. Tests on M107-155mm projectiles indicated that higher thresholds are possible for thick-case, or robust, munitions. Robust munitions are thick-case munitions, sometimes defined as having a nominal wall thickness of at least 1 cm and a ratio of explosive weight to empty case weight less than 1. The M107-155mm projectile and the MK82 bomb are considered thick-case munitions. The projectile is 155mm in diameter (6.1 inches), 23¾ inches in length (without the shock attenuating plug), and has a NEW of 15.5 lbs of Composition B. The MK82 bomb is about 5 ft. long, with a 10¾-inch diameter, a weight of 500 lbs, and a NEW of 192 lbs of H6.

Lagrangian and Eulerian finite element codes, DYNA3D [2] and AUTODYN [3], have been used to predict explosive fill peak stress and case deformation in flyer plate SR tests and NPW tests. Good agreement of predicted deformation and SR was previously obtained for M107-155mm projectiles and MK82 bombs [4, 5]. The effects of key properties, such as mass, velocity, shape of debris, and shape of acceptor can be evaluated by these codes.

Explosives pressure sensitivity tests (such as the Underwater Sensitivity Test, UST), and case crushing tests [4] have been used in the HPM Program to establish sensitivity thresholds for peak explosive fill pressure and case deformation. The predicted acceptor response to

concrete debris impact can use the same peak pressure and case crushing threshold criteria for establishing preliminary SR thresholds versus concrete debris mass and velocity.

3. SCOPE

The critical, i.e. most sensitive, acceptors of each class of munitions was determined under a previous program [4]. It is assumed that if the most sensitive acceptor does not experience sympathetic detonation, then no other acceptor munition in the class will. Among the robust, thick-case munitions, the M107-155mm projectile and the MK82 bomb were determined as critical and analyzed. These acceptors have already been tested in at least two of a series of debris tests, flyer plate tests, and NPW tests.

For the single concrete fragments, two fragment masses were used (4" diameter, 3 lb.; and 12" diameter, 77 lb. spheres) at velocities between 400 ft/s and 1200 ft/s. Sympathetic reaction was based on the mechanical response (peak explosive fill pressure and case deformation) criteria used in the HPM program. For the magazine headwall, two velocities were used, 55.4 and 110.9 ft/s.

4. THRESHOLD RESPONSE CRITERIA

The Underwater Sensitivity Test (UST) and Modified Gap Test (MGT) establish peak pressure thresholds for reaction of explosives. The UST and MGT differ in the manner in which the load is applied, in the resulting load shape and duration, and in resulting reaction threshold pressure values. The longer duration UST gives lower threshold reaction (ignition) pressures, P_{UST} (Table 1). These UST threshold pressures (at which ignition, not detonation, occurs) have been used in the HPM program to establish threshold SR design criteria for preventing SDT. That criteria limits calculated design pressures in the explosive fill to $0.75P_{UST}$ (or 3 Kbar if P_{UST} is not known) [4].

Case crushing thresholds for thick-case munitions (MK82 bombs with H6 fill and M107-155mm projectiles with Composition B fill) have also been determined using flyer plate tests [4]. The ratio of the change in diameter to original diameter of the acceptor, $\Delta D/D$, is limited to 25% to prevent any explosive fill reaction (burning, deflagration, DDT, and XDT). At less than 25% relative deformation, case cracking and rupture is prevented in thick-skin munitions. For thin-case munitions, SR criteria based on peak pressure and applied loads (momentum and energy) is in the development stage in the HPM program [6].

Response to debris impact was categorized as a function of relative deformation and predicted explosive fill pressure. The analytical models developed peak pressures exceeding the threshold for SDT only at very high velocities. The criteria used to indicate the relative response or reaction was based on test data and analysis and is shown in Table 2.

5. DEBRIS CHARACTERIZATION

Typical debris characteristics (mass, size, and velocity) were researched in the literature. Schwartz reports measured concrete debris velocities, from tests of standard dividing walls, between 400 and 800 ft/s [7]. URS fragment tests on NWC Standard Dividing Wall Acceptors were conducted at velocities between 330 and 930 ft/s [1]. Independent tests on M107-155mm projectiles used velocities between 425 and 1170 ft/s [8]. The HPM NPW velocities are predicted to be between 200 and 450 ft/s. In order to span the range of design velocities for NPW's and concrete debris, this study considered velocities between 200 and 1200 ft/s.

The URS tests used standard rubble charges (Mk-1 rubble) containing about 50 lb. of concrete fragments and 25 lb. of 3/8 to 3/4-inch aggregate, for a total weight of 70 to 75 lbs (Table 3). The concrete fragments varied in size from 1 to 8 inches [1]. In tests by Rindner et al., rubble masses of 125 to 250 lb. were used [8]. In addition, single concrete projectiles (fragments) with masses between 55 and 480 lb. were also utilized (Tables 4a and 4b).

The current fragment study is limited to the effects of single concrete fragment impacts on the acceptors. Two large spherical sizes were chosen: (1) a 4-inch diameter concrete fragment, weighing about 3 lbs, and (2) a 12-inch diameter concrete fragment, weighing about 77 lbs. The 12-inch, 77-lb single fragment has approximately the total mass of the standard URS Mk-1 rubble but will yield conservative results for being in a single piece.   Many of the Rindner tests (Table 4) used larger masses. However, a 12 inch diameter piece of concrete is considered large for a single piece from a NPW. The 3-lb. and 77-lb. single concrete fragments used in this study will be conservative for multiple debris impacts with a total mass less than or equal to the single fragment mass. Although results of the 77 lb. fragment impact should apply conservatively to many NPW scenarios, additional research should be conducted to determine typical characteristics of concrete debris (e.g. mass, size, shape), and additional analyses should be conducted for these additional parameters, as well as for multiple fragment impact.

6. HEADWALL IMPACT

Non-standard earth-covered magazines are being evaluated for increased storage limits without compromising explosive safety [9]. The main concern is prevention of sympathetic detonation between magazines. This sympathetic detonation is mainly dependent upon the sensitivity of the acceptor munitions, and the mass and velocity of the secondary fragments in the acceptors' magazine. Secondary fragments from the headwalls are potentially most damaging.

Among the robust, thick-case munitions, the M107-155mm projectile and the MK82 bomb were determined as critical [9]. Since the MK82 bomb could be easily stored beyond the current explosive weight limits for non-standard earth-covered magazines, the numerical analyses concentrate on this munition. If only this type of munition is stored, it is expected that the current 250,000 lbs limit for non-standard earth-covered magazines could be increased to 500,000 lbs without compromising safety. This storage weight is now allowed for non-standard earth-covered magazines.

The maximum secondary fragment velocity in a magazine headwall can be conservatively calculated by assuming that the headwall has no resistance. The headwall velocities for various magazine NEW limits and wall thicknesses were derived. The maximum velocity was 110.9 ft/s for a 6" thick wall, and 55.4 ft/s for a 12" thick wall [9].

For the headwall study, only the critical thick-cased MK82 bomb was considered as an acceptor. Previous studies [5] have shown that aligning several acceptors with their axes of symmetry parallel to the wall, as in a pallet, yields conservative results for explosive fill pressure and case deformation. Additionally, modeling only three adjacent, in-line acceptors is sufficient to capture a typical acceptor response. This can be verified if successive impacts do not increase the permanent plastic deformation of the first acceptor. It was finally assumed that most of the headwall kinetic energy would have dissipated by the time the end of the magazine is reached, so no backwall was placed behind the acceptors.

In modeling the wall, it was decided to conservatively assume the wall intact upon impact with the acceptors. This would produce a worst case loading, as more impulse is then transferred to the acceptors. The magazines surveyed [9] were oval, with a main diameter around 26 ft. It was decided to model a 26 ft. by 13 ft. rectangular wall hitting the acceptors. The highest reinforcement of #5 bars at 6" on centers (each way, each face) was used, since more reinforcing would insure more momentum transfer to the acceptors.

7. FINITE ELEMENT ANALYSES

The Lawrence Livermore National Laboratory explicit Lagrangian finite element program DYNA3D [2] was used in the study. The concrete fragments were modeled as spheres with an initial velocity. The material model used to represent concrete was developed concurrently under sponsorship of the Defense Nuclear Agency [10,11,12]. This model represents a complete revision of the existing material 16 (concrete/ geological material), with significant improvements in tension, compression and rate behaviors. In particular, as the fragment starts to crack, the original model would instantaneously lose all its strength, both in tension and compression. In the revised model, a post-cracking strain softening model is used, together with a fracture energy localization limiter to preclude any mesh size dependency, and cracked elements can still carry compression. Steel reinforcement was modeled using discrete truss elements and an elastic plastic material model. Explosive fill properties were obtained from the Navy Explosives Handbook [13].

8. DEBRIS IMPACT RESULTS

Table 5 summarizes the calculated acceptor deformations and peak explosive fill pressures resulting from the impact of a concrete fragment (4-inch and 12-inch diameter) at velocities from 400 to 1200 ft/s. Expected reactions, based on the SR criteria defined (Table 2), are also given. Any predicted reaction in a thick case munition could potentially transition to a

detonation. Susan tests performed on the explosives used in these munitions have shown that Composition B is somewhat more sensitive than H6 [14].

8.1 M107-155mm Predictions

The model used for the thick case M107-155mm projectile is shown in Figure 1a with a 3-lb, 4-inch fragment. The analysis showed that in general the M107-155mm projectile will not react unless under severe conditions (Table 5). A 4-inch fragment will only slightly deform this acceptor and produce no reaction within the usual range of debris velocities. At 400 ft/s (Figure 1b) and 800 ft/s, the concrete fragment will fracture and flow around the acceptor. This is in agreement with test results [8].

Calculations show that a 77-lb., 12-inch fragment would possibly crack the case and produce a burn beyond 800 ft/s (Figure 1c). With a rigid wall behind the acceptor, this burn could occur around 600 ft/s (Figure 1d). The threshold pressure is only exceeded at velocities in excess of 1000 ft/s. Figures 1e and 1f show complete three-dimensional views of the analyses. Figures 1g and 1h show the permanent deformations in the acceptor.

Figure 2a shows the deformation versus time history of the M107-155 at two central locations due to a 12-inch fragment at 400 ft/s. The peak deformation is relatively small (6.8%) and a significant part of it is recovered elastically. Figure 2b indicates the corresponding fill pressures at 6 locations, 3 on the impact side and 3 on the back side. Figures 2c and 2d report the same information for a velocity of 1200 ft/s. The elastic recovery at this higher velocity is insignificant and the peak deformation is 34.1%. Pressures at 6 locations are again reported, the largest one being 3.3 Kbar.

8.2 Comparison with Rindner's tests

Tests results by Rindner et al. on M107-155mm projectile (Composition B fill) are summarized in Table 4. Table 4a reports results at ambient temperature, whereas Table 4b shows results with the Comp B fill heated at 150°F [15]. In most tests single solid concrete projectiles, or fragments, were used. The fragments weighed from 50 to 480 lbs each. Since the projectile used in the numerical simulations had a mass of 77 lbs, predictions are compared to results using the 50-lb or 55-lb masses. These masses were projected at velocities from 370 to 1170 ft/s. At ambient temperature and velocities up to 1170 ft/s only casing deformation was observed, with no reaction (Table 4a). At 150°F, the 155mm acceptor could react at a velocity of about 900 ft/s (Table 4b).

The numerical predictions for a single 77-lb debris fragment indicated a burning threshold of 600 ft/s with a rigid backwall behind the acceptor (conservative case), and 800 ft/s without a backwall (as in the test program). Hence the model and reaction criteria conservatively predict the actual response at ambient temperature (part of this conservatism is due to the different mass). For acceptors at elevated temperature (150°F) a closer prediction is obtained.

8.3 MK82 Bomb Predictions

The finite element model for the thick-case MK82 bomb is shown in Figures 3 and 4. Calculations indicated that reaction will only occur under severe conditions. As for the M107-155mm projectile, a 77-lb, 12-inch fragment would crack the case and produce a reaction at velocities around 800 ft/s. With a rigid wall behind the acceptor (worst case condition), this reaction could occur at 600 ft/s. Although detonation was only predicted to occur at 1200 ft/s, it could take place upon case cracking due to DDT or XDT transition. Figures 3a and 3b show the bomb deformations for 12-inch fragment at velocities of 400 and 1200 ft/s, respectively. Figure 4 shows the three-dimensional model just prior to contact, at peak deformation, and finally emphasizes the calculated permanent bomb deformation. In practice, the bomb would have burned or exploded prior to reaching this deformation.

9. HEADWALL IMPACT RESULTS

Figure 5 shows the undeformed finite element model for impact from the headwall. Figure 5b is a section through the plane of symmetry of the undeformed mesh detailing the explosive fill and rebar location. In all runs the headwall thickness was set at 12". In the first analysis the headwall velocity was set at 55.4 ft/s. Figure 6a shows the case deformation (relative diameter change), which is less than 1%. This is well below the 25% threshold. It should be noted that impact with bomb 3 does not result in an additional permanent plastic deformation for bomb 1 (beyond the deformation due to impact with bomb 2). This indicates that successive impacts would result only in elastic deformation. The peak explosive fill pressure was about 0.3 Kbar, well below the 4.8 Kbar threshold (Figure 6b). A second numerical analysis using the same mesh but twice the velocity (110.9 ft/s) was then completed, yielding peak deformations of less than 2.5% and peak fill pressures of about 0.5 Kbar.

The low predicted damage from the magazine headwall (at relatively low velocity) is consistent with the MK82 resistance to high impact velocities from single concrete fragments, as previously shown. These results are also consistent with previous experience with crush tests on MK82 bombs. These tests showed that the bombs could withstand the impulse from 3,000-lb steel plates at velocities of up to 587 ft/s (179 m/s) with the additional constraint of a 6,000-lb back plate [4]. A crusher plate consisting of several 1" layers of steel and polyethylene reduced the initial contact pressures. Numerical models of these crush tests yielded conservative predictions of the test results. It is expected that the current analyses will also yield conservative results.

10. CONCLUSIONS

Preliminary sympathetic detonation criteria for single concrete fragment impact have been developed numerically for two thick-case acceptors, a MK82 bomb and a M107-155mm projectile. Reaction threshold predictions appeared conservative in comparison with test results

available for the M107-155mm projectile. The analyses predicted that the two munitions could withstand velocities of at least 600 ft/s, with the additional restraint of a rigid back wall, before any reaction took place. The data seem to indicate that even in these severe loading cases, reactions would probably be in the form of case rupture and fill burn for usual debris sizes and velocities. If no back wall is present, no sympathetic reaction of these munitions is likely for large, 77-lb fragments at velocities below 800 ft/s.

The response of three-inline MK82 bombs to impact from a reinforced concrete headwall was evaluated. The acceptors were able to sustain lateral impact at the highest velocity of 110.9 ft/s, representative of a 500,000-lb explosive limit in an adjacent earth-covered magazine. For the cases studied no sympathetic detonation was expected.

11. FUTURE WORK

The present analyses have not considered additional parameters such as different concrete fragment shape, mechanical properties, and multiple debris fragments. Other acceptor types should also be analyzed and additional validation testing should be conducted before a final criteria is proposed.

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TABLE 1. IGNITION THRESHOLDS

MATERIAL	UST (Kbar)	MGT (Kbar)	RATIO UST/MGT
COMP B-3 (b)	5.5	17.0	0.324
60/40 CYCLOTOL (c)	4.7	14.5	0.324
H-6 (b)	6.4	18.4	0.348
LX-04-1	9.0	25.9	0.347
PBX 9404-3	6.0	18.0	0.333
PBXN-109	6.1	18.6	0.328
PENTOLITE (c)	4.7	12.1	0.388
AFX 108E	5.1		
25/75 CYCLOTOL (b)	6.7		
PBXC-117	5.1		
PBXC-121	7.8		
PBXN-103	8.9		
PBXW-113 II	5.9		
HBX-1	15.5 (a)	45.9	0.339 (d)
HBX-3	15.5 (a)	45.7	0.339 (d)
PBXN-110	8.8 (a)	26.0	0.339 (d)
PBXN-111	8.1 (a)	24.0	0.339 (d)
TETRYL	5.1 (a)	15.2	0.339 (d)

(a) calculated from P_{MGT} using $P_{UST} = 0.339 \, P_{UST}$ (c) pressed

(b) cast   (d) assumed

TABLE 2. THRESHOLD DEFINITION

THRESHOLD		EXPECTED REACTION	
DEFORMATION	PRESSURE	THICK-CASE	THIN-CASE
$\Delta D/D < 0.12$	$P \leq 0.75\ P_{UST}$	NO REACTION	NO REACTION
$0.12 \leq \Delta D/D < 0.25$	$P \leq 0.75\ P_{UST}$	NO REACTION	PROBABLE BURN
$0.25 \leq \Delta D/D$	$P \leq 0.75\ P_{UST}$	PROBABLE BURN POSSIBLE EXP/DET*	PROBABLE BURN
-	$0.75\ P_{UST} \leq P$	PROBABLE EXP/DET*	POSSIBLE EXP/DET*

* Explosion/Detonation

TABLE 3. NWC STANDARD ACCEPTOR TEST RESULTS*

DEBRIS TYPE	WEIGHT (lbs)	VELOCITY (ft/s)	STANDARD ACCEPTOR		WITHOUT DETONATOR	
			TESTS	DET**	TESTS	DET**
rubble	35	220-250	0		2	0
rubble	70	300-349	2	0	5	0
rubble	70	350-399	0		5	3
rubble	70	400-449	4	1	4	2
rubble	70	450-499	8	4	8	5
rubble	70	500-549	10	7	4	2
rubble	70	700-850	7	7	2	2

 * adapted from [1], standard acceptor without detonators
 ** high-order detonation as per [1]

TABLE 4a. 155 MM PROJECTILE TEST RESULTS*

DEBRIS TYPE	NUMBER OF TESTS	PROJECTILE WEIGHT (lbs)	PROJECTILE VELOCITY (ft/s)	RESULTS
solid	3	480	350-360	slight damage
solid	2	380	425-500	no damage
solid	2	380	545-550	slight damage
solid	3	180	560	small deformation
solid	2	55	1170	casing deformation
rubble	8	125-250	525-680	slight damage

* adapted from [8]

TABLE 4b. 155 MM PROJECTILE TEST RESULTS AT 150°F *

DEBRIS TYPE	NUMBER OF TESTS	PROJECTILE WEIGHT (lbs)	PROJECTILE VELOCITY (ft/s)	REACTION
solid	2	50	890	HO**, no go
solid	1	50	564	initial flash
solid	1	50	370	no go
solid	3	185	500-650	no go
solid	4	375	400-550	no go
rubble	3	175	570-750	no go

* adapted from [15]
** High Order detonation, as per [15]

TABLE 5. NUMERICAL PREDICTIONS FOR SINGLE CONCRETE DEBRIS IMPACT

ACCEPTOR TYPE	FRAGMENT SIZE AND SPEED Analysis with (+w) or without backwall	PRESSURE		FRAGMENT MOMENTUM	ΔD/D RELATIVE DEFORMATION		FRAGMENT KINETIC ENERGY	PREDICTED REACTION
		Peak (Kbar)	$0.75P_{UST}$ (Kbar)	MV (lbs-ft/s)	Peak (%)	Threshold (%)	(kips-ft^2/s^2)	
M107-155mm projectile (CompB)	4" @ 400 ft/s	0.33	4.1	1200	0.30	25	240	none
	4" @ 800 ft/s	0.38	4.1	2400	1.10	25	960	none
	12" @ 400 ft/s	0.82	4.1	30800	6.80	25	6160	none
	12" @ 800 ft/s	1.92	4.1	61600	23.2	25	24640	possible burn
	12" @ 1200 ft/s	3.26	4.1	92400	34.1	25	55440	burn
	12" @ 400 ft/s + w	0.80	4.1	30800	10.7	25	6160	none
	12" @ 600 ft/s + w	1.78	4.1	46200	24.1	25	13860	possible burn
	12" @ 800 ft/s + w	2.88	4.1	61600	35.1	25	24640	reaction*
	12" @ 1000 ft/s+ w	3.43	4.1	77000	43.2	25	38500	reaction*
	12" @ 1200 ft/s+ w	4.35	4.1	92400	50.3	25	55440	detonation
MK82 bomb (H6)	4" @ 400 ft/s	0.55	4.8	1200	0.60	25	240	none
	12" @ 400 ft/s + w	1.62	4.8	30800	11.2	25	6160	none
	12" @ 600 ft/s + w	2.34	4.8	46200	23.7	25	13860	possible burn
	12" @ 800 ft/s + w	3.31	4.8	61600	35.0	25	24640	reaction*.
	12" @ 1000 ft/s+ w	4.07	4.8	77000	43.8	25	38500	reaction*
	12" @ 1200 ft/s+ w	4.98	4.8	92400	50.2	25	55440	detonation

* Reaction = burn/explosion/detonation
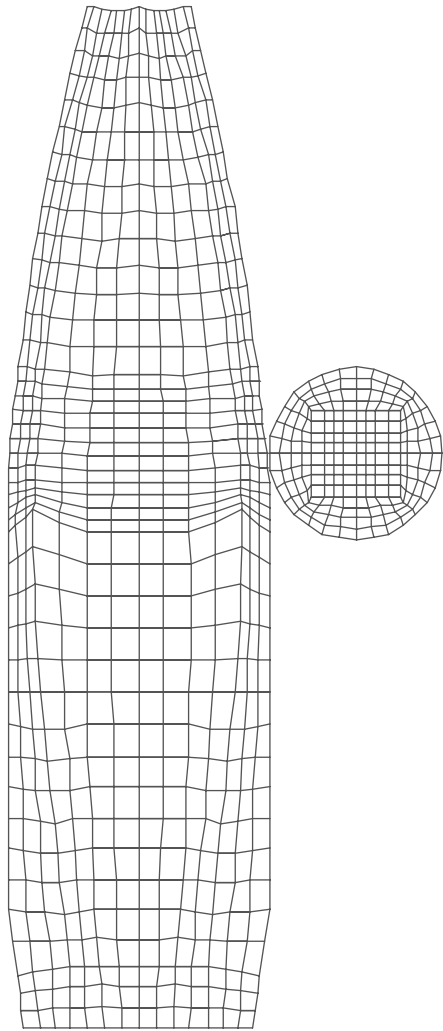
Figure 1a. M107-155mm discretization.
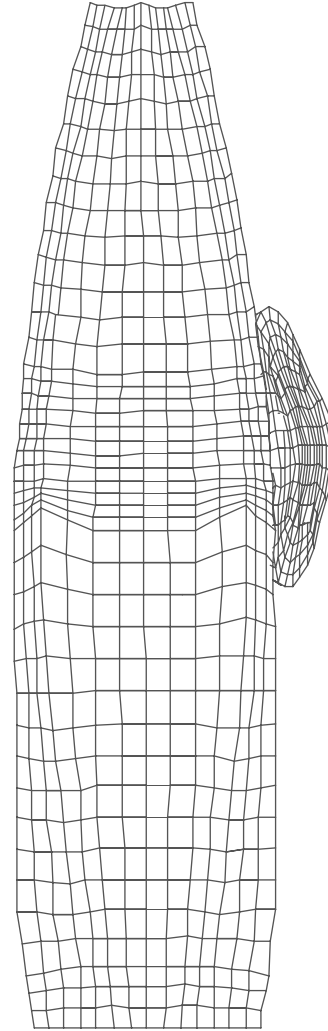
Figure 1b. Effect of 4" debris at 400 ft/s.
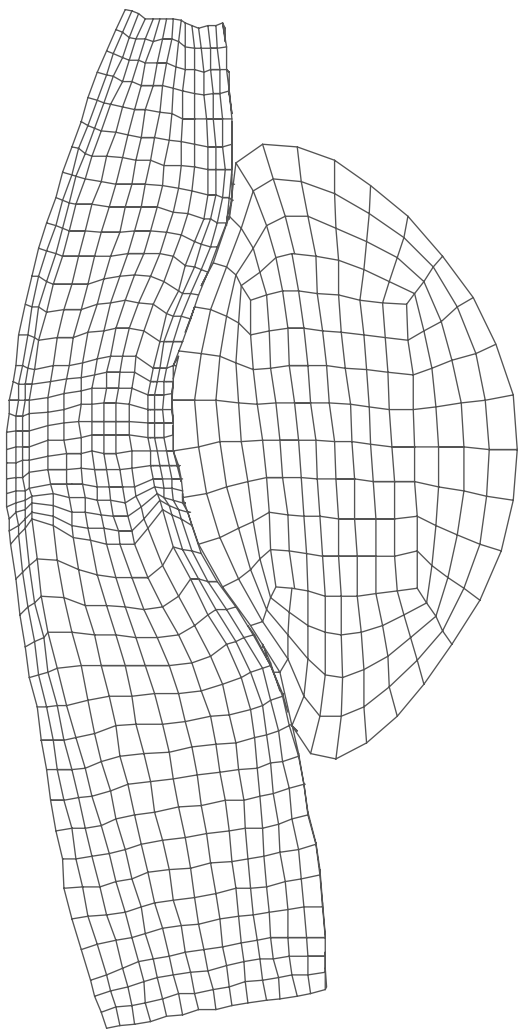
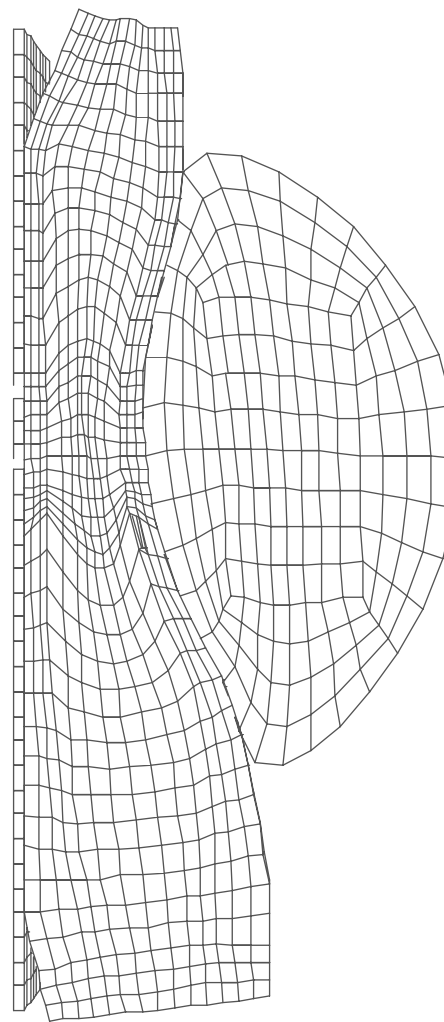Figure 1c. Effect of 12" debris at 1200 ft/s

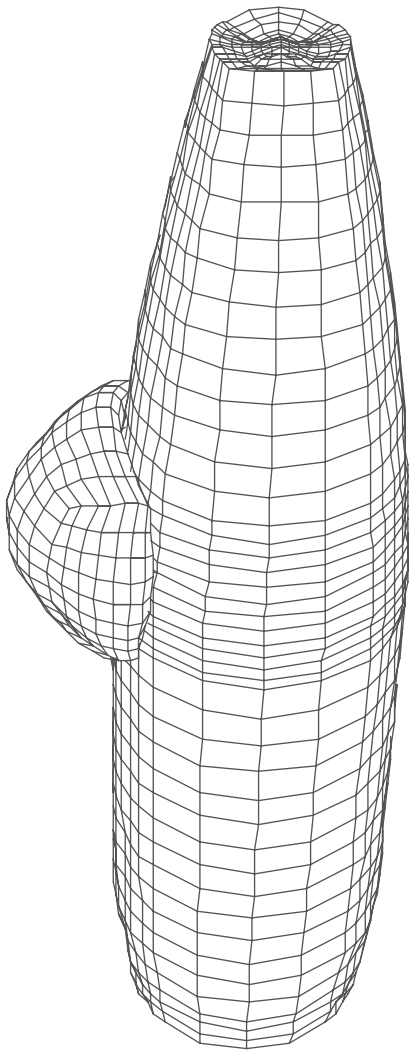Figure 1d. Back wall and 12" debris at 1200 ft/s

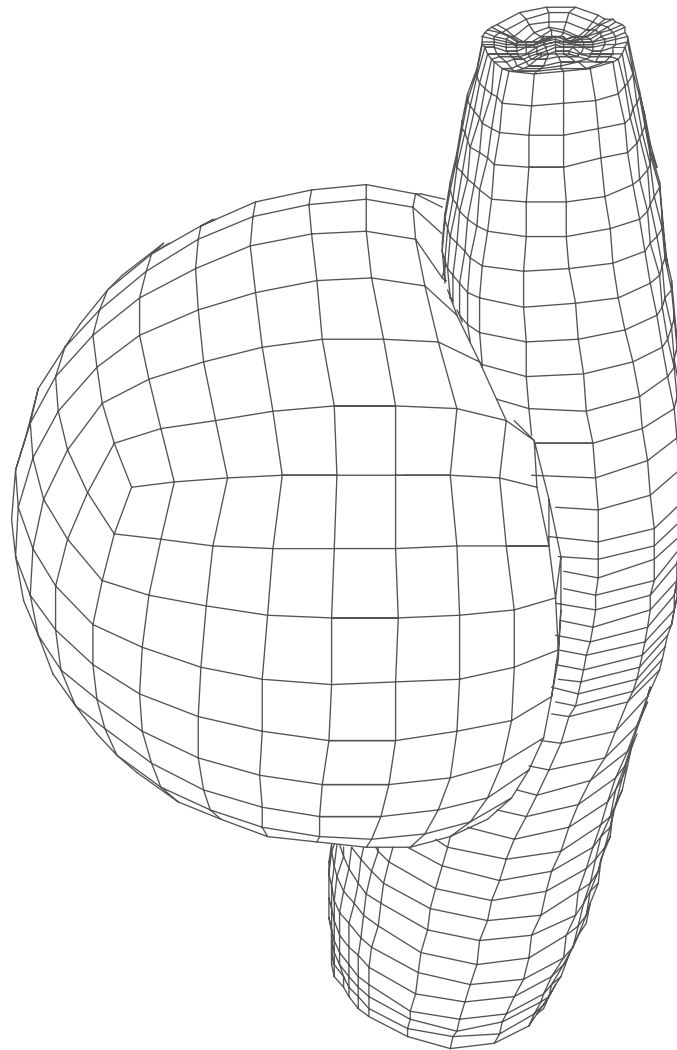Figure 1e. Effect of 4" debris at 400 ft/s
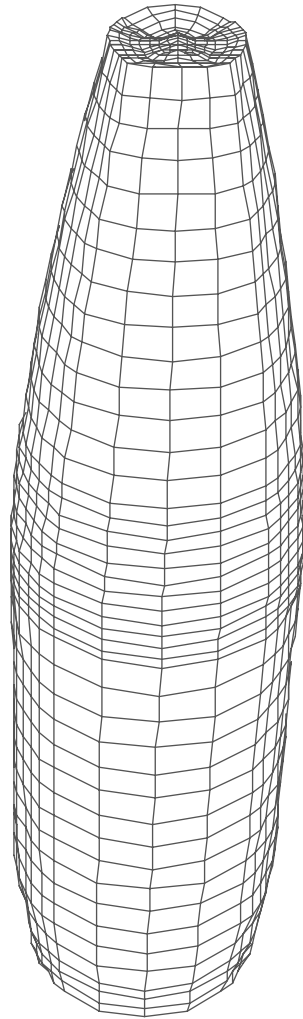

Figure 1f. Effect of 12" debris at 1200 ft/s

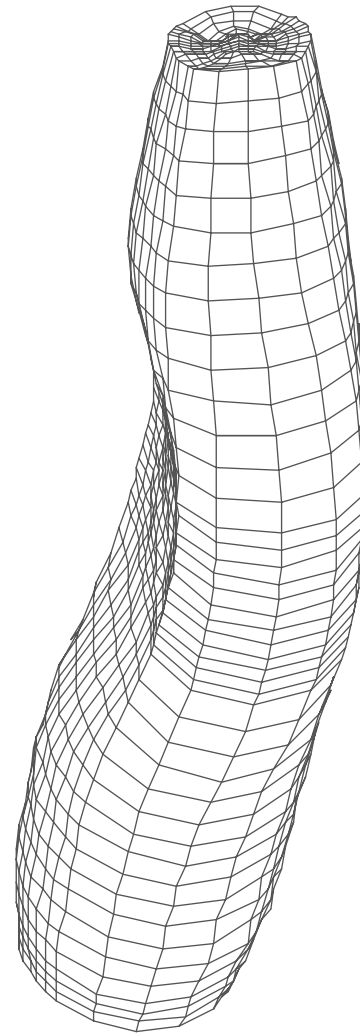Figure 1g. Effect of 4" debris at 400 ft/s:
Projectile deformation

Figure 1h. Effect of 12" debris at 1200 ft/s:
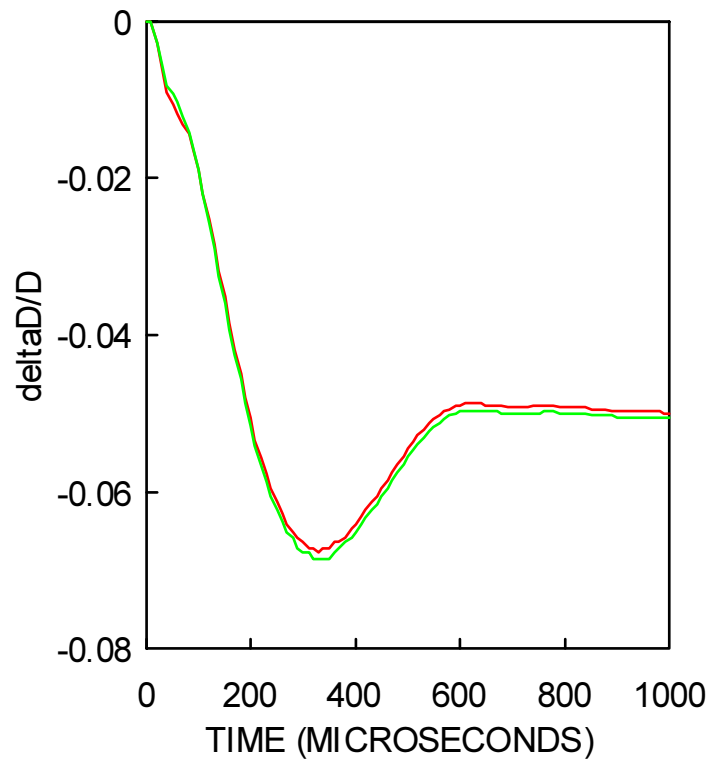Projectile deformation

Figure 2a. Relative deformation ΔD/D, 12" debris at 400 ft/s on projectile.
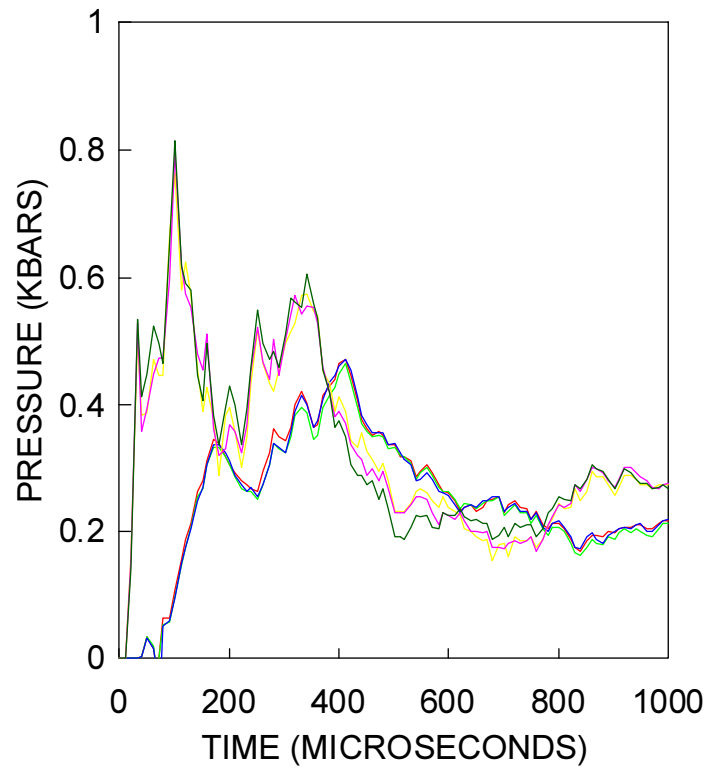
Figure 2b. Fill pressure, 12" debris at 400 ft/s on projectile.
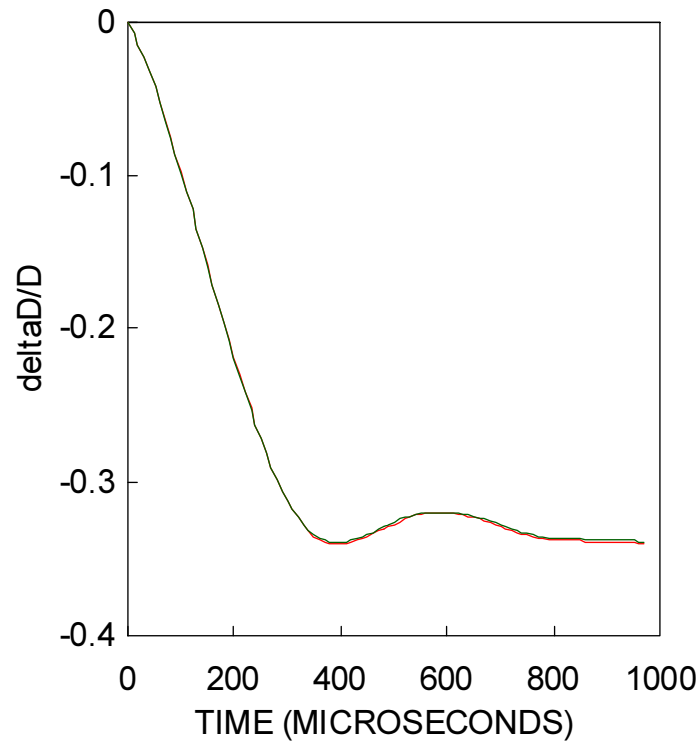
Figure 2c. Relative deformation ΔD/D, 12" debris at 1200 ft/s on projectile.
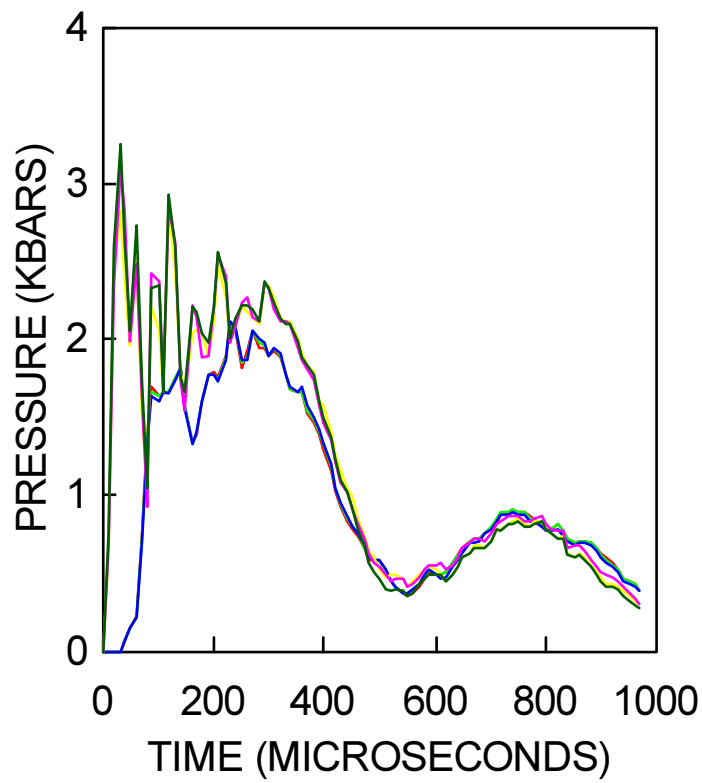
Figure 2d. Fill pressure, 12" debris at 1200 ft/s on projectile.
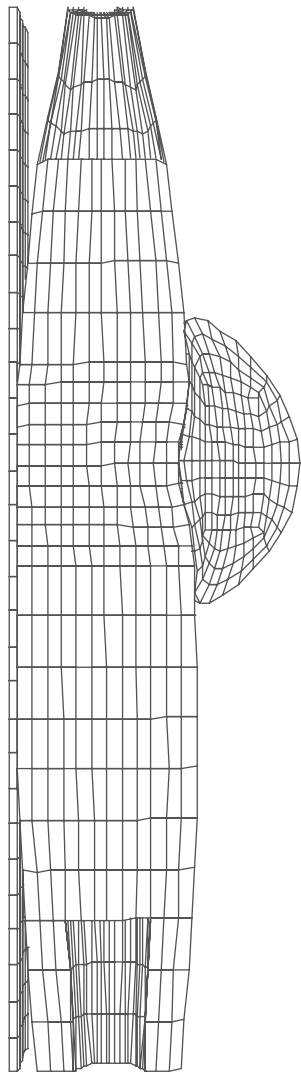
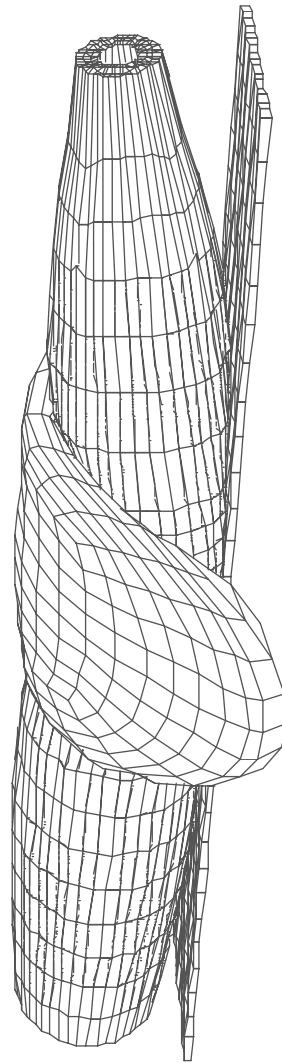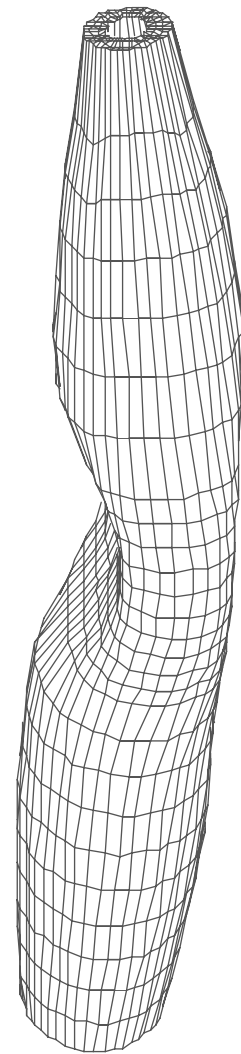Figure 3a. Effect of 12" debris at 400 ft/s on MK 82 bomb.
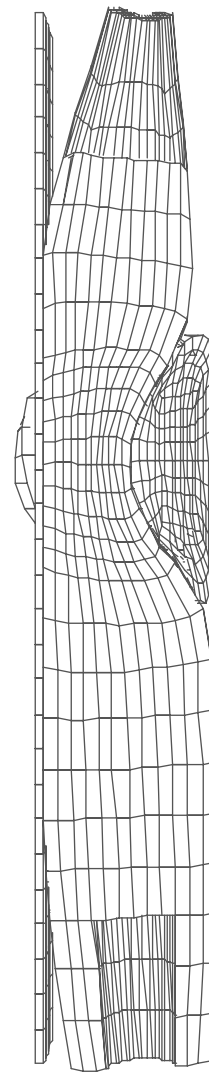
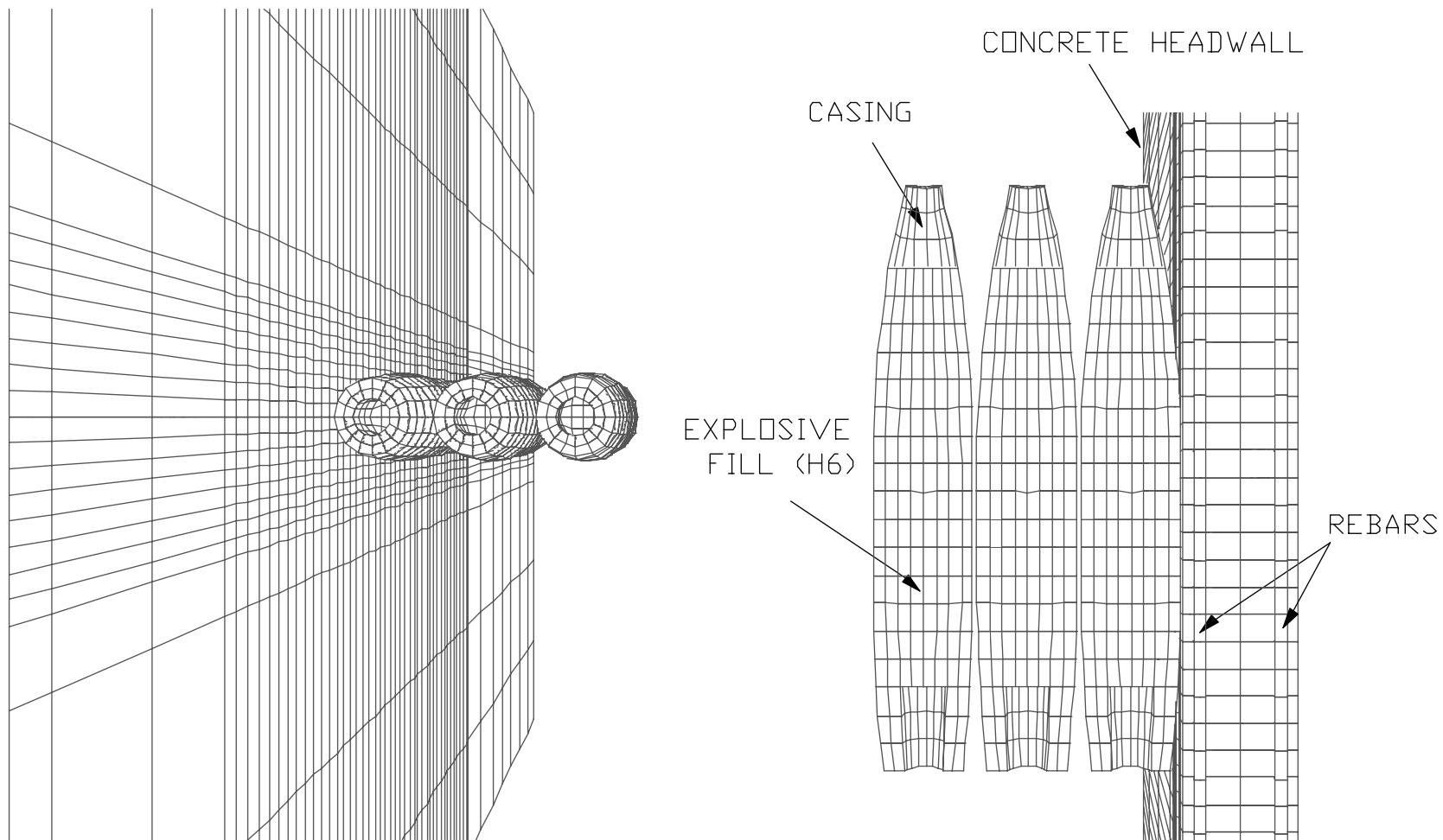Figure 3b. Effect of 12" debris at 1200 ft/s on MK82 bomb.
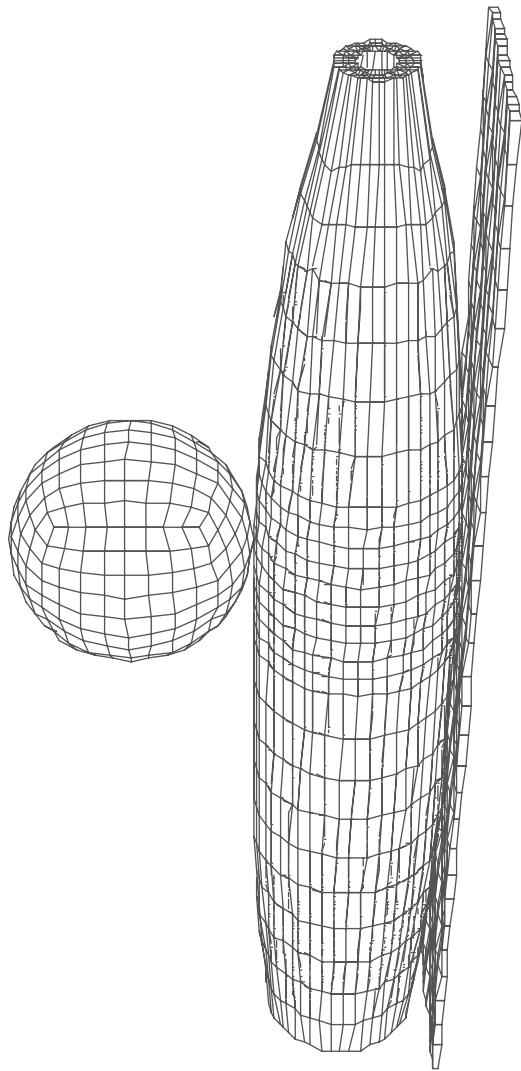
(a) Undeformed shape   (b) Shape at peak bomb deformation   (c) Bomb deformation.
Figure 4. Effect of 12" debris on MK82 bomb.

CONCRETE HEADWALL

CASING

EXPLOSIVE
FILL (H6)

REBARS

a) Three dimensional model   b) Undeformed section through symmetry plane

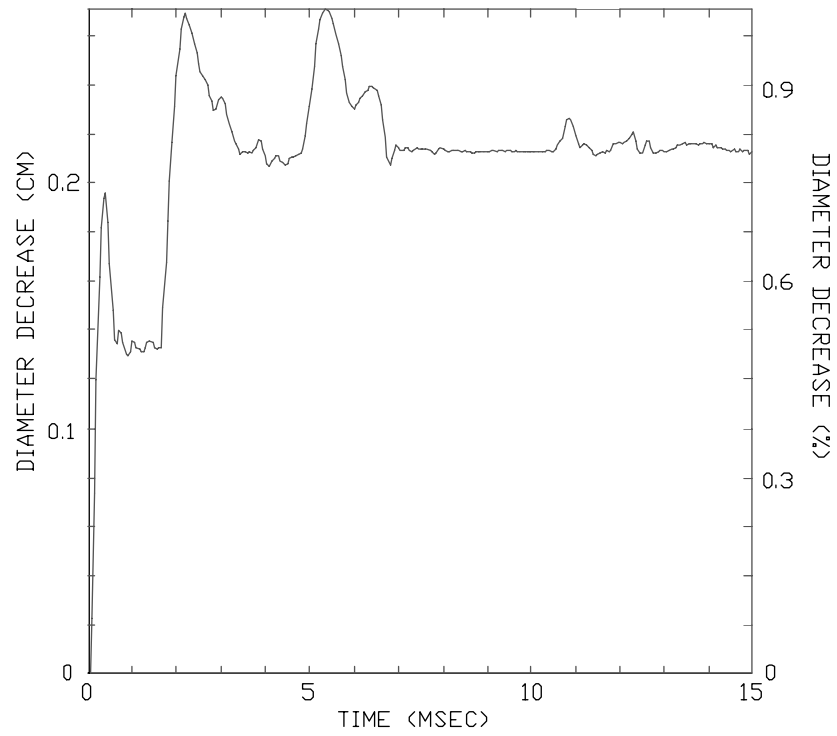Figure 5. Headwall impact on three MK82 acceptors.

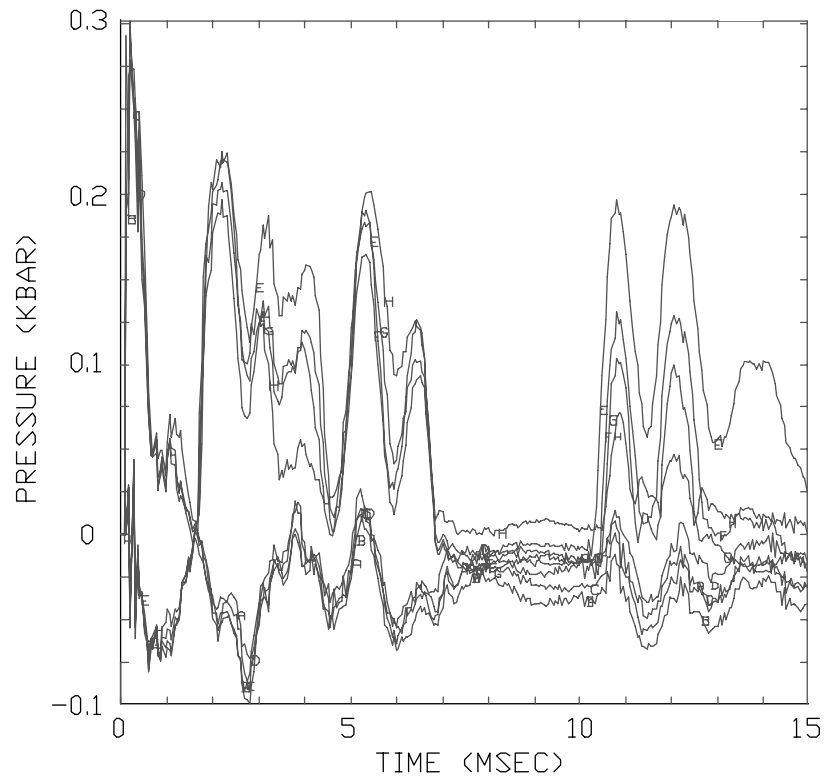Figure 6a. Headwall impact: diameter decrease versus time, bomb 1.

Figure 6b. Headwall impact: pressure time histories, bomb 1.